Cosmology with the Sunyaev-Zel`dovich Effect

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Outline

(1) Some background: the CMB, inverse Compton scattering, galaxy clusters

(2) The Sunyaev-Zel`dovich Effect

(3) Cosmological probes

(4) Upcoming SZ observational campaigns

(5) Simulations of the SZE

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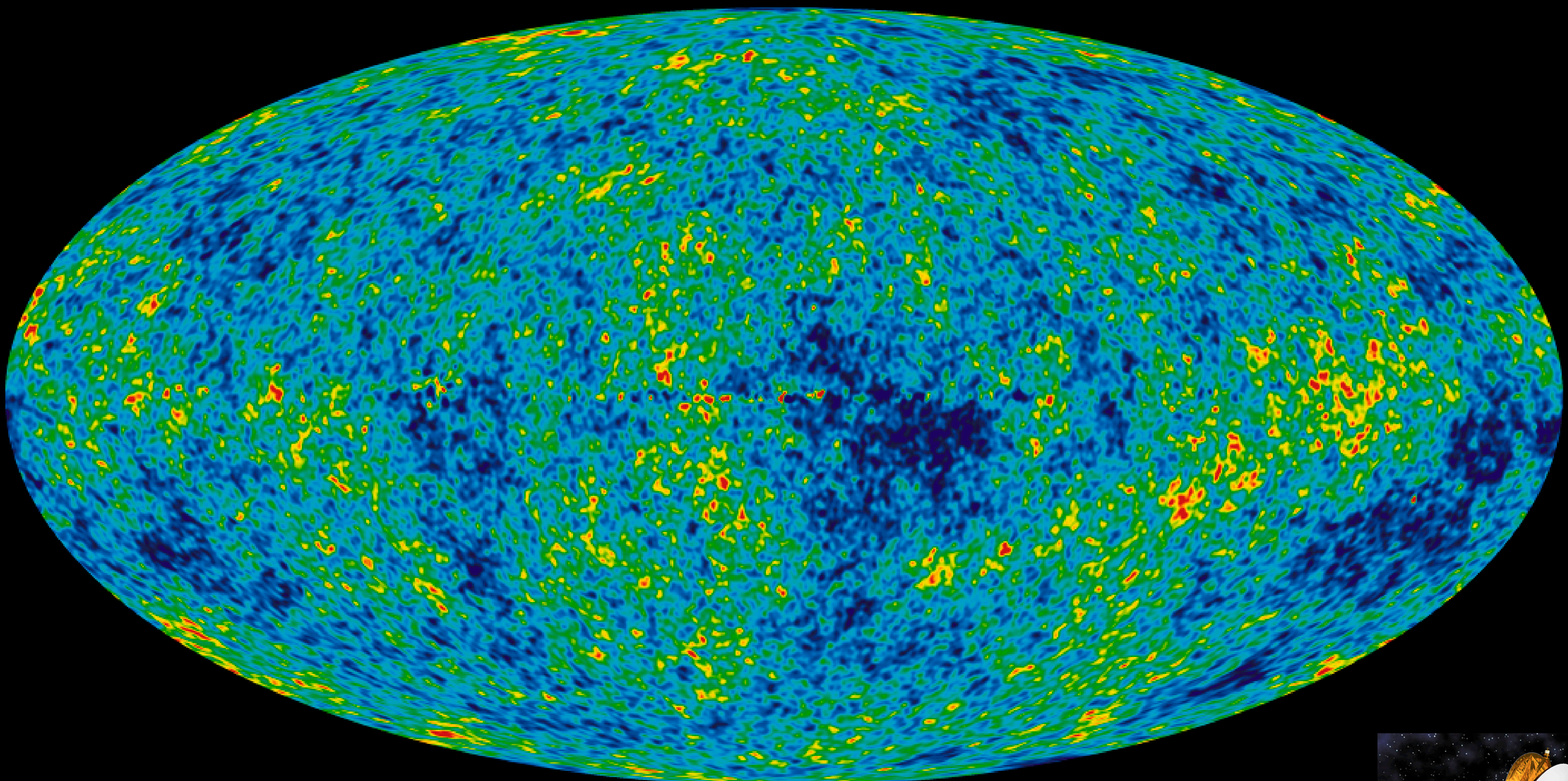
The cosmic microwave background

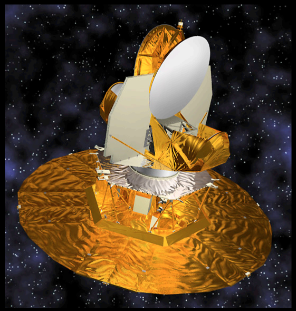
- high-z ($z \gtrsim 10^3$) universe was ionized, opaque due to Thompson/Coulomb scattering
- as T dropped below ≈ 3,000 K, hydrogen recombined and became mostly neutral
- photon mean free path went up significantly - universe became effectively transparent!

The cosmic microwave background



WMAP Year 3 data release

image c/o NASA/WMAP science team



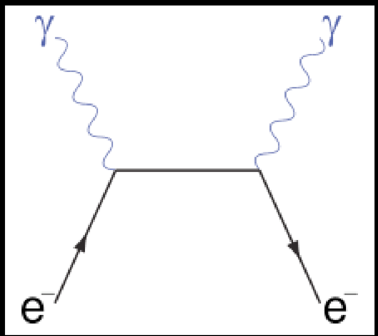
The cosmic microwave background

- The CMB is nearly a perfect blackbody
- Acoustic peaks in CMB cause tiny fluctuations in temperature, but are still blackbody in spectrum
- There are many sources of secondary anisotropies which cause deviations from blackbody
- The CMB provides a background light source for these!
- These secondary anisotropies can be used to tell us many useful things about the universe!

(Example: the Sunyaev-Zel`dovich effect!)

Inverse Compton scattering

- Nearly elastic photon-baryon scattering (photon-electron in the case we care about)
- Causes an increase of energy of a photon when it interacts with matter
- interaction in the limit of $k_b T_e \gg h\nu$
- Very important process in many aspects of astrophysics



Single photon:

$$\varepsilon' = \frac{\varepsilon}{1 + (\varepsilon/m_e c^2)(1 - \cos\phi_{12})}$$

Inv. Compton scattering: population of photons

Incident spectrum

$$I_0(\nu) = \frac{2h\nu^3}{c^2}(\mathrm{e}^{h\nu/k_B T_{\mathrm{rad}}} - 1)^{-1}$$

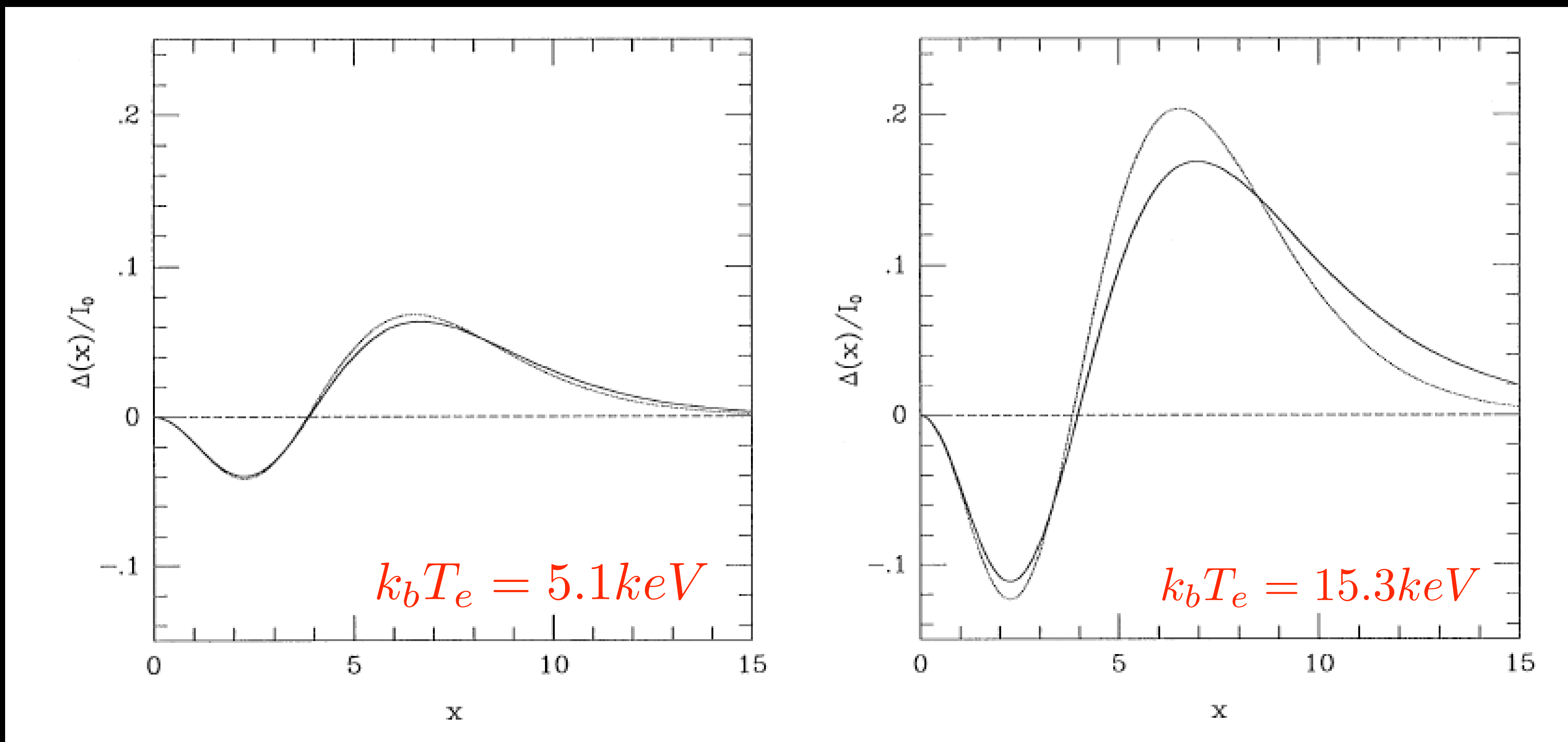
Output spectrum if all photons scattered once

$$\frac{I(\nu)}{\nu} = \int_0^{\infty} \mathrm{d}\nu_0 \, P_1(\nu, \nu_0) \frac{I_0(\nu_0)}{\nu_0}$$

$$\Delta I(\nu) \equiv I(\nu) - I_0(\nu) = \frac{2h}{c^2} \int_{-\infty}^{\infty} P_1(s) \, \mathrm{d}s \left(\frac{\nu_0^3}{\mathrm{e}^{h\nu_0/k_B T_{\mathrm{rad}}} - 1} - \frac{\nu^3}{\mathrm{e}^{h\nu/k_B T_{\mathrm{rad}}} - 1} \right)$$

$P_1(s)$ = frequency shift function

Planck spectrum scattered by thermal dist'n of electrons



$$x = \frac{h\nu}{k_bT_{rad}} = 0.0176\frac{\nu}{GHz}$$

Note: assumes all photons scattered once!

Galaxy clusters

- Discussed in great detail by Christoph on Tuesday (3 July)
- Largest gravitationally-bound objects in the universe
- Primarily composed of dark matter + hot (10^7-10^8 K) intracluster gas (also some galaxies)
- $M_{char} \sim 10^{14}$-10^{15} $M_\odot$, $R_{char} \sim$ 1-few Mpc, $\langle n_b \rangle \sim 10^{-4}$

Galaxy clusters

- Lots of interesting astrophysics going on inside galaxy clusters (c.f. Pfrommer talk)
- HOWEVER, to first order we're interested in galaxy clusters as a "big bag of gas"
- For most of talk, assume gas is approximately in hydrostatic equilibrium (not a great assumption)
- Will discuss how variations from HSE affect results later

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The Sunyaev-Zel`dovich Effect

- Spectral distortion of the CMB caused by the scattering of CMB photons off of high-energy electrons
- Two components of SZ: thermal and kinetic
- SZE can also be polarized (though contribution is small)
- Original papers: Sunyaev & Zel`dovich 1970 (Comm. Astrophys. Space Phys. 2:66-74), 1972 (Comm. Astrophys. Space Phys. 4:173-78)

Thermal SZE

- Inverse Compton scattering of CMB by thermal electron population in ICM
- Optical depth of a cluster is:

$$\tau_e \simeq n_e \sigma_T L \sim 10^{-4} - 10^{-3}$$

- only tiny fraction of CMB photons scatter - small fractional distortion of CMB!

The thermal SZE

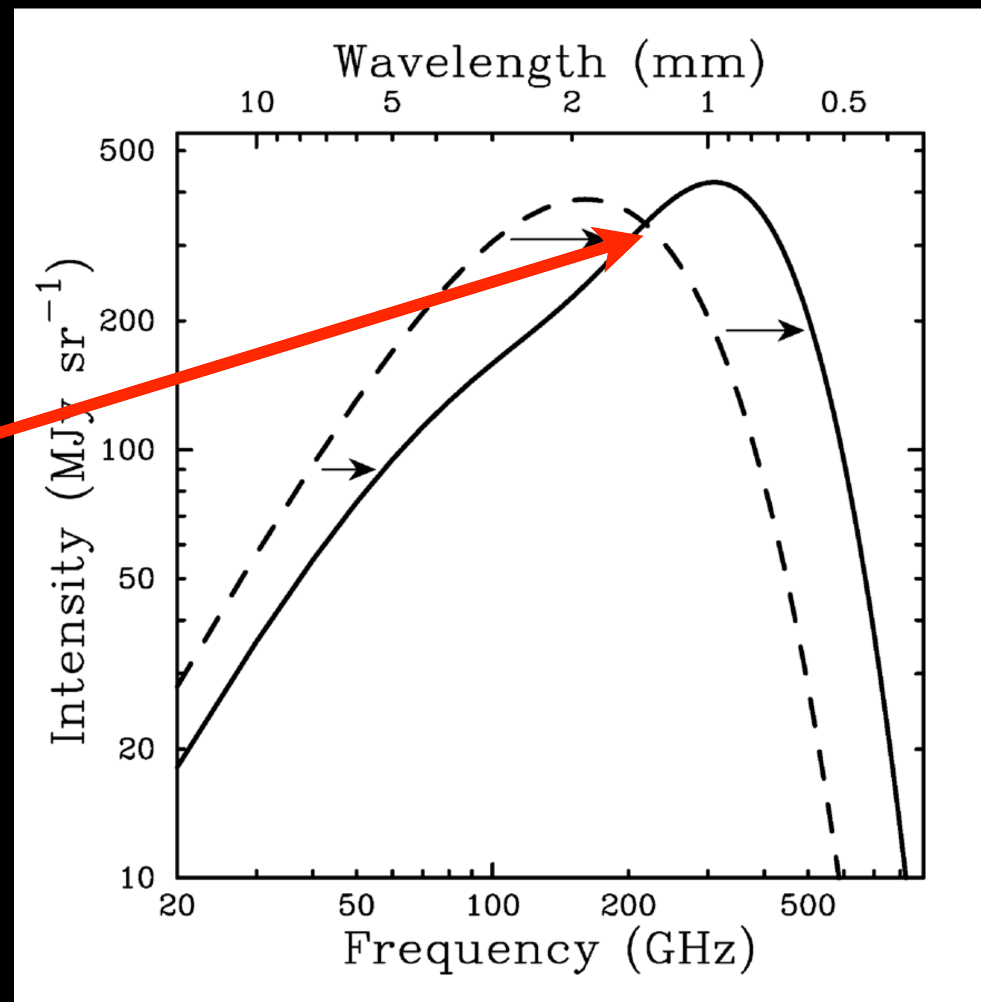
$$x \equiv \frac{h\nu}{k_B T_{CMB}}$$

$$\frac{\Delta T_{SZE}}{T_{CMB}} = f(x)\, y = f(x) \int n_e \frac{k_B T_e}{m_e c^2} \sigma_T \, d\ell$$

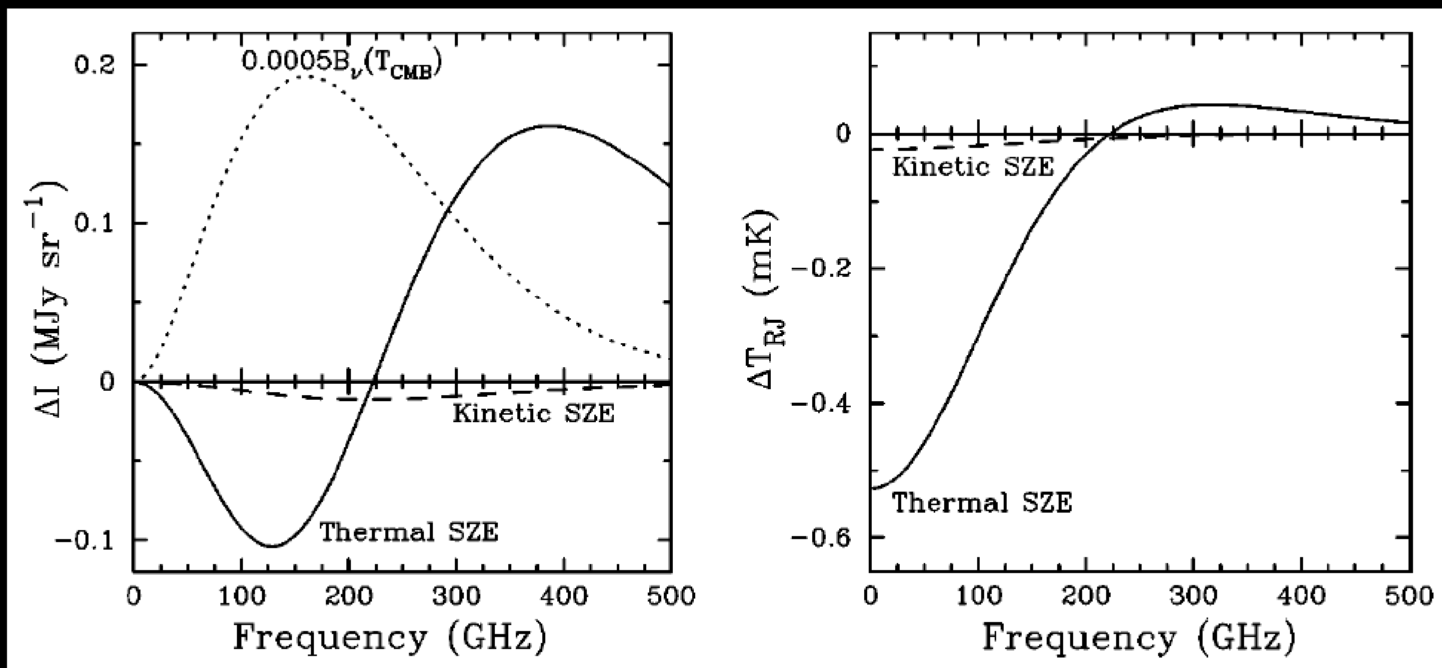
$$f(x) = \left(x \frac{e^x + 1}{e^x - 1} - 4 \right) (1 + \delta_{SZE}(x, T_e)),$$

Thermal SZE: spectral distortion

zero point ~ 218 Ghz



Thermal SZE spectral distortion



Change in CMB intensity

Change in RJ brightness temperature

The integrated SZE signal

- Very important for finding clusters with an SZE survey
- Integrating over solid angle of cluster gives temperature-weighted measure of cluster electron content (and thus total thermal energy of cluster)

$$d\Omega = dA / D_{\mathrm{A}}^2$$

$$\int \Delta T_{SZE} \, d\Omega \propto \frac{N_e \langle T_e \rangle}{D_{\mathrm{A}}^2} \propto \frac{M \langle T_e \rangle}{D_{\mathrm{A}}^2}$$

Useful features of thermal SZE

- small spectral distortion of CMB which is proportional to cluster pressure along LOS
- redshift-independent
- unique spectral signature (easy to extract from back/foregrounds)
- integrated SZE flux prop. to temperature-weighted mass of cluster (mass threshold *nearly* independent of redshift)

Kinetic SZE

- a.k.a. "Ostriker-Vishniac Effect" (O&V 1986, ApJ, 306, L51)
- If cluster is moving w.r.t. CMB rest frame, there is an additional spectral distortion due to Doppler effect of cluster bulk velocity on CMB
- LOS component of v_{pec} causes apparent change in CMB temperature!
- Kinetic SZE is still blackbody spectrum (in the nonrelativistic limit), but slightly different temperature
- This effect is rather tiny compared to thermal SZE

$$\frac{\Delta T_{SZE}}{T_{CMB}} = -\tau_e \left(\frac{v_{pec}}{c}\right)$$

SZE polarization

- Scattering of CMB photons by ICM can result in linear polarization
- This is due to anisotropic optical depth to a given location in the cluster
- more specifically, this is due to the quadrupole component of the local radiation field (motion of cluster transverse to LOS, electron optical depth, scattering off thermal photons)

SZE polarization

- Sunyaev & Zel`Dovich (1980, MNRAS 190: 413-420), Sazonov & Sunyaev (1999, MNRAS, 310, 765-72) - analytic spherical dist'n of clusters
  - largest terms go as $\sim\tau_e(v_{pec,\perp}/c)^2$ and $\sim\tau^2{}_e(v_{pec,\perp}/c)$ in CMB intensity.
  - Optimistically, polarization levels of ~10 nK can be reached (too small!)
- Shimon et al. 2006, MNRAS 368, 511-517
  - when hydro + dm cosmological simulations are analyzed (non-symmetric, non-ideal clusters) one finds that scattering due to thermal electrons is more important than other terms
  - polarization levels of ~1 μK may be seen! (possibly observable)

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The SZE as a cosmological probe

- SZE is redshift-independent find clusters at wide range of z w/different selection function from other observational techniques
- Measures LOS pressure ($n_e T_e$) instead of more complicated function of n_e, T_e: insensitive to cluster physics, so robust mass estimator (?)
- Can be combined with other obs. techniques to trace structure formation at the high-mass halo end from z ~2-3 to present day!

$$\frac{\Delta T_{SZE}}{T_{CMB}} = f(x)\, y = f(x) \int n_e \frac{k_B T_e}{m_e c^2} \sigma_T \, d\ell$$

Possible cosmological probes

1. Galaxy cluster mass function/abundance evolution
2. Hubble constant and cosmological distance determination
3. Cluster gas mass fraction
4. Cluster peculiar velocities

Galaxy cluster mass function/ abundance evolution

Press-Schechter mass function:

$$\frac{dn(M,z)}{dM} = -\sqrt{\frac{2}{\pi}}\,\frac{\bar{\rho}}{M^2}\,\frac{d\ln\sigma(M,z)}{d\ln M}\,\frac{\delta_c}{\sigma(M,z)}\exp\left[\frac{-\delta_c^2}{2\sigma^2(M,z)}\right]$$

$\bar{\rho}$ = mean density of universe at present day

M = mass of halo

n = comoving number density

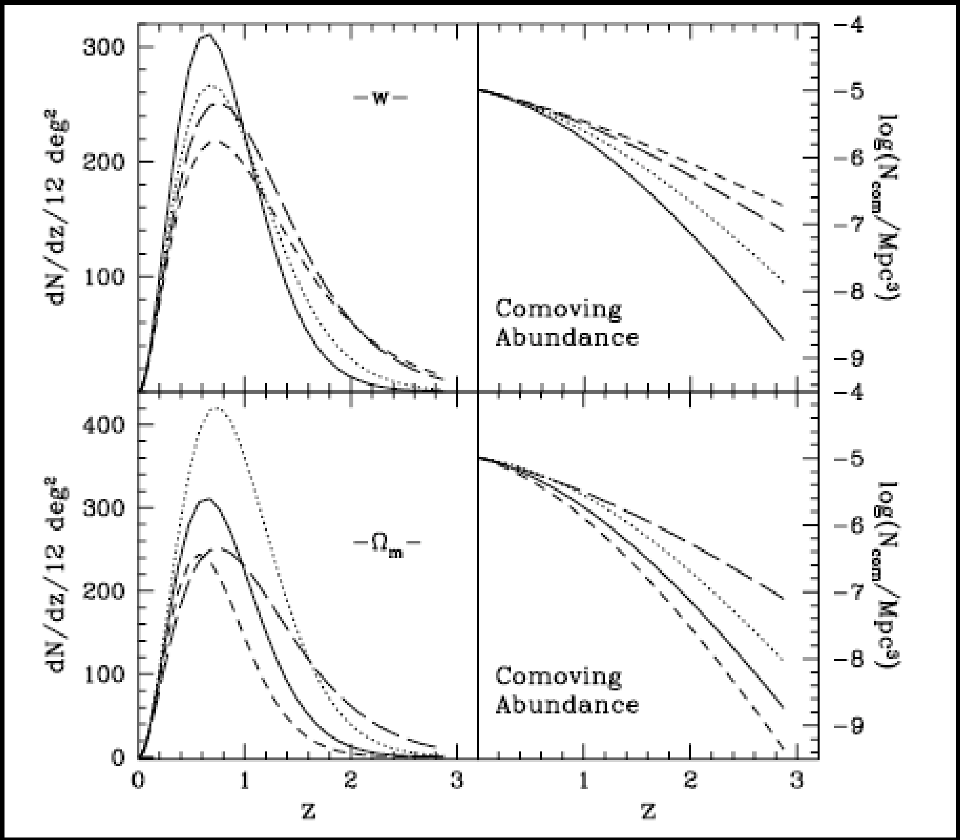
$\sigma(M,z) = \sigma(M)D(z)$ = (variance of density field) x (linear growth function)

$\delta_c \simeq 1.69 =$ critical dens. for collapse in spherical collapse model

Galaxy cluster mass function/ abundance evolution

- Galaxy cluster population is exponentially sensitive to cosmology
- Measuring, e.g., N(>M) as a function of redshift is a very sensitive probe of cosmological parameters!
- Caveat 1: this requires a combination of SZE, some other measurements
- Caveat 2: also requires robust mass estimator (see later in talk)

Example: variation in w, Ω_m on results of an SZE survey



solid: w=-1, Ω_m=0.3, h=0.65
dotted, short-dashed:
w = -0.6, -0.2
long-dashed: OCDM, Ω_m=0.3

solid: w=-1, Ω_m=0.3, h=0.65
dotted, short-dashed:
Ω_m= 0.27, 0.33
long-dashed: OCDM, Ω_m=0.3

sfc density of clusters

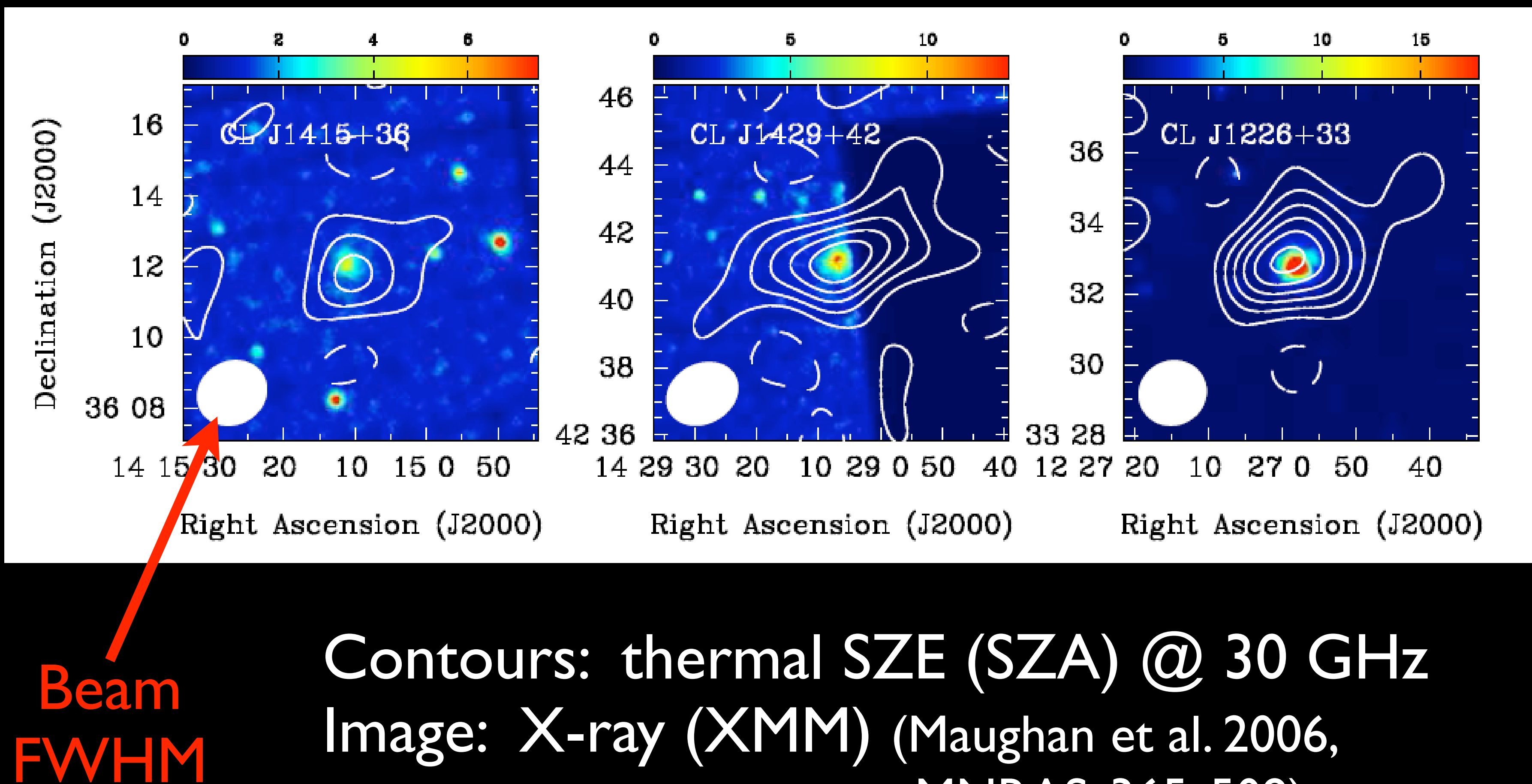
comoving cluster abundance

see Haiman, Mohr & Holder 2001, ApJ, 553: 545-561

First results: The Sunyaev-Zel`dovich Array (SZA)

- Muchovej et al. 2007 (ApJ, in press; astro-ph/0610115)
- Three clusters w. z = 0.89-1.03 observed at 30 GHz during commissioning period of the SZA interferometer (at BIMA site)
- Derive cluster masses assuming isothermality, hydrostatic equilibrium

First results: The Sunyaev-Zel`dovich Array (SZA)



Contours: thermal SZE (SZA) @ 30 GHz

Image: X-ray (XMM) (Maughan et al. 2006, MNRAS, 365, 509)

First results: The Sunyaev-Zel`dovich Array (SZA)

Table 6. Comparison of SZ and X-ray Derived Temperature and Masses

Cluster Name	$R^{X-ray}_{\Delta(z)}$	R (Mpc)	θ_c [b] ($''$)	SZ Derived Quantities T_e (keV)	SZ Derived Quantities M_{gas} ($10^{12} M_\odot$)	SZ Derived Quantities M_{total} ($10^{13} M_\odot$)	X-ray Masses[a] T_e (keV)	X-ray Masses[a] M_{gas} ($10^{12} M_\odot$)	X-ray Masses[a] M_{total} ($10^{13} M_\odot$)
Cl J1415.1+3612	$R_{2500(z)}$	0.23	11.7	$3.7^{+0.8}_{-0.7}$	$6.2^{+1.5}_{-0.9}$	$5.6^{+1.3}_{-1.0}$	$5.7^{+1.2}_{-0.7}$	$6.7^{+1.2}_{-1.2}$	$8.8^{+3.1}_{-2.5}$
			[8.5, 30]	$3.7^{+0.8}_{-0.8}$	$5.6^{+1.8}_{-0.8}$	$5.1^{+1.0}_{-1.3}$			
	$R_{200(z)}$	0.88	11.7	$3.7^{+0.8}_{-0.7}$	$38.2^{+9.2}_{-5.5}$	$24.3^{+5.5}_{-4.3}$	$5.7^{+1.2}_{-0.7}$	$38.5^{+5.4}_{-4.3}$	$38.3^{+12.0}_{-9.4}$
			[8.5, 30]	$3.7^{+0.8}_{-0.8}$	$38.9^{+10.3}_{-6.3}$	$24.0^{+5.1}_{-5.1}$			
Cl J1429.0+4241	$R_{2500(z)}$	0.26	12.4	$5.5^{+0.7}_{-1.0}$	$10.8^{+1.2}_{-2.0}$	$8.9^{+1.7}_{-1.1}$	$6.2^{+1.5}_{-1.0}$	$7.3^{+1.5}_{-1.6}$	$10.5^{+4.8}_{-3.3}$
			[8.5, 30]	$5.2^{+0.9}_{-0.7}$	$9.5^{+2.0}_{-1.7}$	$8.6^{+1.7}_{-1.8}$			
	$R_{200(z)}$	0.97	12.4	$5.5^{+0.7}_{-1.0}$	$62.2^{+6.7}_{-11.2}$	$39.7^{+4.9}_{-6.7}$	$6.2^{+1.5}_{-1.0}$	$42.9^{+7.6}_{-6.0}$	$44.9^{+17.3}_{-1.29}$
			[8.5, 30]	$5.2^{+0.9}_{-0.7}$	$62.7^{+8.7}_{-11.3}$	$37.9^{+6.0}_{-6.0}$			
Cl J1226.9+3332	$R_{2500(z)}$	0.35	14.6	$8.9^{+1.2}_{-1.5}$	$23.7^{+3.6}_{-3.3}$	$20.9^{+2.8}_{-3.2}$	$10.6^{+1.1}_{-1.1}$	$21.5^{+1.9}_{-2.2}$	$25.0^{+4.6}_{-4.3}$
			[8.5, 30]	$8.3^{+1.8}_{-0.8}$	$23.7^{+3.0}_{-4.7}$	$20.6^{+3.3}_{-3.7}$			
	$R_{200(z)}$	1.29	14.6	$8.9^{+1.2}_{-1.5}$	$130.2^{+19.6}_{-18.3}$	$84.7^{+11.5}_{-11.5}$	$10.6^{+1.1}_{-1.1}$	$119.0^{+8.9}_{-8.2}$	$102.0^{+17.1}_{-16.8}$
			[8.5, 30]	$8.3^{+1.8}_{-0.8}$	$130.4^{+21.1}_{-21.1}$	$80.3^{+14.6}_{-10.1}$			

[a]reproduced from Maughan et al. (2006)

[b]Prior on core radius, for SZ-derived quantities

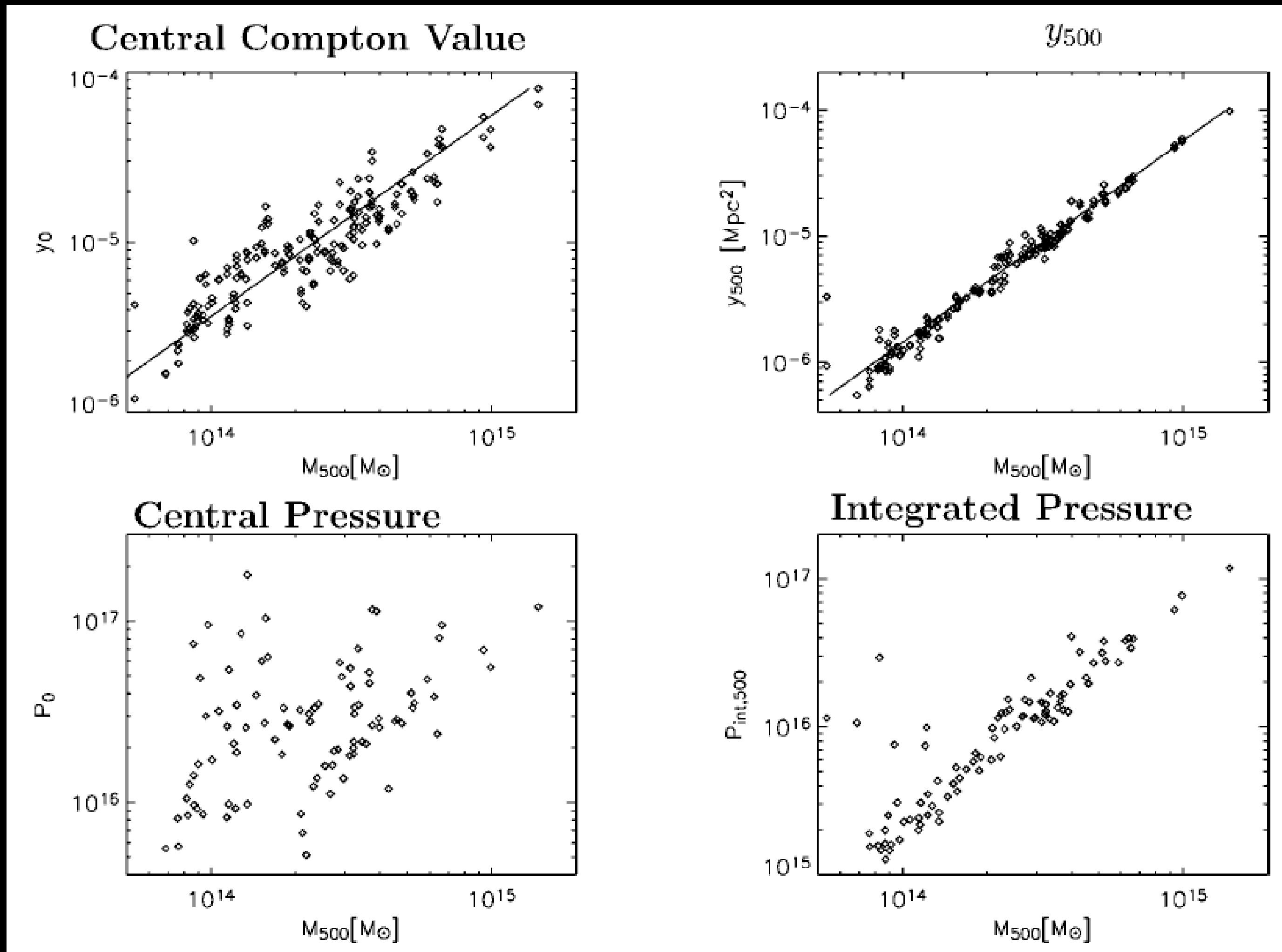
Aside: calculating cluster masses from observables

- Accurate determination of cosmological parameters requires precise knowledge of cluster mass function n(>M, z)
- This requires a well-understood relationship between M_{gas}/M_{tot} and at least one SZE observable (y_0, y_{500}, etc.)
- This observable-mass relationship must be reliable at 1) moderate resolution and 2) for a huge number of clusters (10^3-10^4 or more)

Aside: calculating cluster masses from observables

- Historically, galaxy cluster masses deduced by using X-ray temperature or X-ray luminosity
- This is problematic for SZE surveys: X-ray telescope time is scarce, and lots of scatter for low-mass clusters
- SZE: possible observables are y_0, y_{500} (or some other integrated y value). What sort of scatter do we observe?

Motl et al. 2005, ApJ, 623, L63-66



$10^{14} \lesssim M_{cl} \lesssim 2\text{x}10^{15}\ M_\odot$

Motl et al. 2005, ApJ, 623, L63-66

TABLE 1

Scaling Exponent for y_{500}-M Relation, $z = 0$

Simulation	α	σ_α
Adiabatic	1.59	0.021
Radiative cooling	1.71	0.031
Star formation	1.60	0.027
Star formation with feedback	1.61	0.024

Scaling depends on physics included in sims
(baryonic physics important)

y_{500}-M seems most accurate scaling relation

TABLE 2

Accuracy of Mass Estimation, $z = 0$

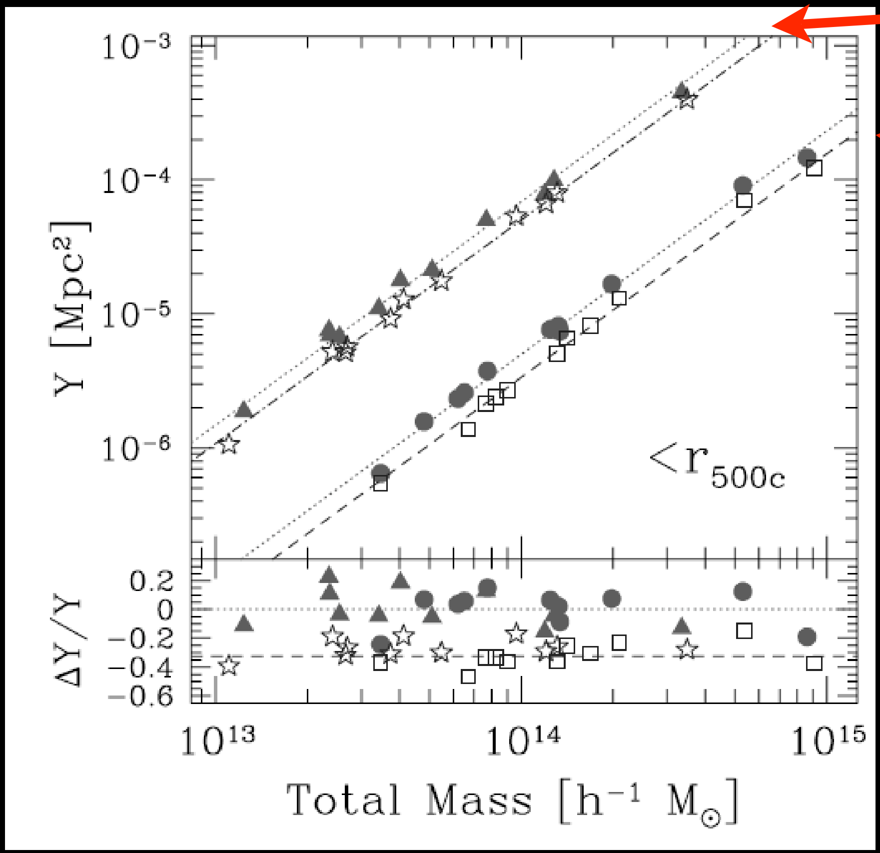
Method	Median M_{est}/M_{true}	$+1\,\sigma$	$-1\,\sigma$	+80%	−80%
y_{500}-M	0.97	1.00	0.93	1.13	0.86
T_X-M	1.04	1.11	0.92	1.33	0.74
$L_{X,500}$-M	0.87	1.03	0.75	1.46	0.62
y_0-M	0.96	1.14	0.82	1.53	0.67

$10^{14} \lesssim M_{cl} \lesssim 2\text{x}10^{15}\ M_\odot$

Nagai 2006, ApJ, 650, 538-49

Self-similar SZE scaling relation

$$Y^{\rm int} \propto \begin{cases} f_{\rm gas} M^{5/3} E^{2/3}(z) \\ f_{\rm gas} T^{5/2} E^{-1}(z) \end{cases}$$



z=1

z=0

Filled points: adiabatic
Open: star formation+FB

Deviation from best fit to adiabatic runs

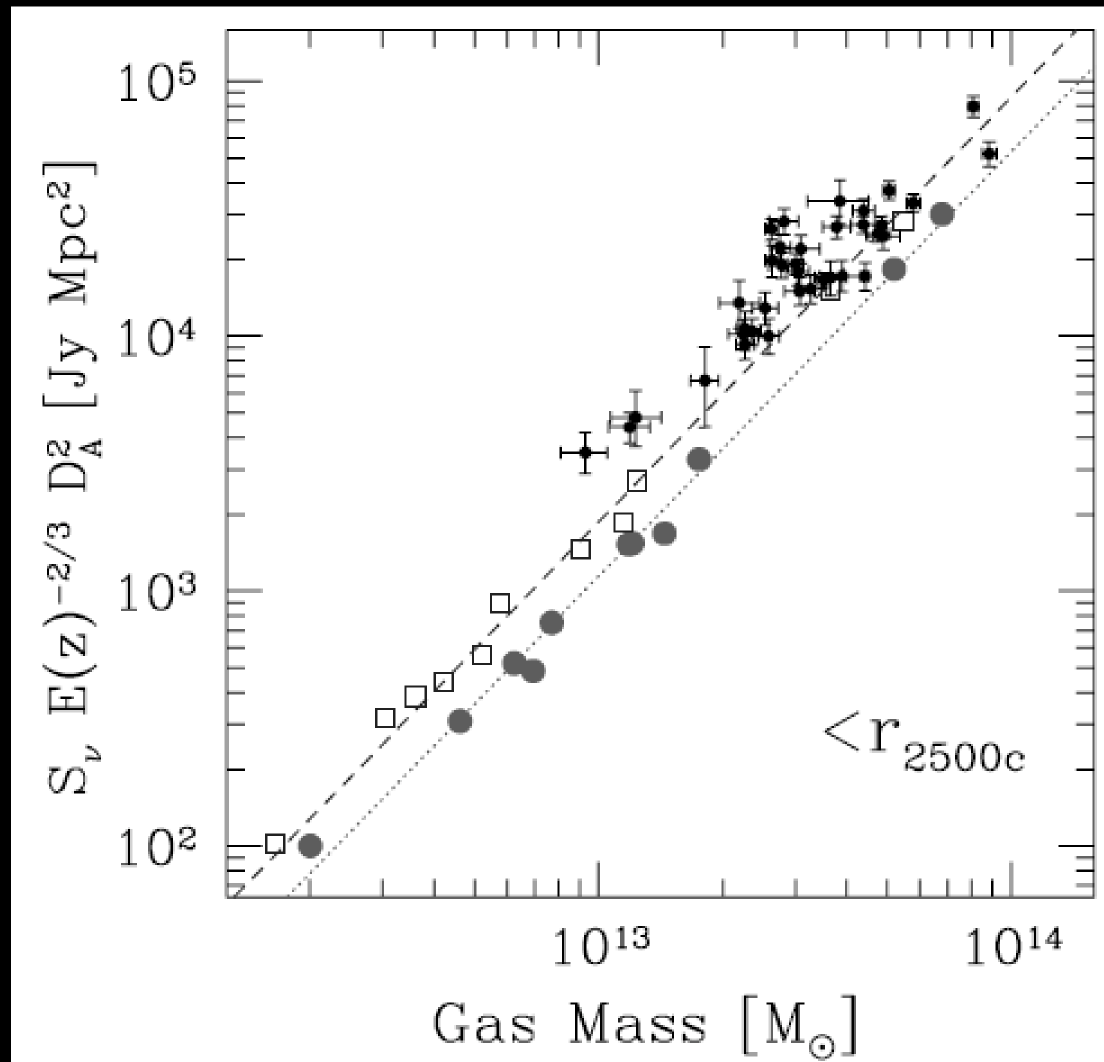
Nagai 2006, ApJ, 650, 538-49

Points w/error bars: LaRoque 2005 (35 clusters, 0.14 < z < 0.89)

open squares: cooling +SF/FB sims

filled circles: adiabatic sims

Note: using gas mass within r_{2500}



Hubble constant, cosmological distance determination

- Distance to a galaxy cluster can be determined using a combination of SZE and X-ray emission (Cavaliere et al. 1977, Gunn et al. 1978, Birkinshaw 1979, etc.)
- Use different density dependencies of SZE, X-ray emission!

$$\Delta T_{SZE} \sim \int d\ell n_e T_e \qquad S_x \sim \int d\ell n_e^2 \Lambda_{eH}$$

Hubble constant, cosmological distance determination

See Birkinshaw & Hughes (1994), Reese et al. (2000) for detailed derivations

say $d\ell = D_A d\zeta$

so, $\Delta T_{CMB,0} \sim n_{e,0} T_{e,0} D_A \int d\zeta$

and $S_{X,0} \sim n_{e,0}^2 \Lambda_{eH0} D_A \int d\zeta$

and thus, $D_A \sim \dfrac{\Delta T_{CMB,0}^2 \Lambda_{eH0}}{S_{X0} T_{e0}^2} \dfrac{1}{\Theta_c}$

$\Theta_c =$ cluster scale along LOS

"0" subscripts: through center of cluster

$D_A + z_{cl} + k =$ Hubble parameter!

Two assumptions made in distance determinations!

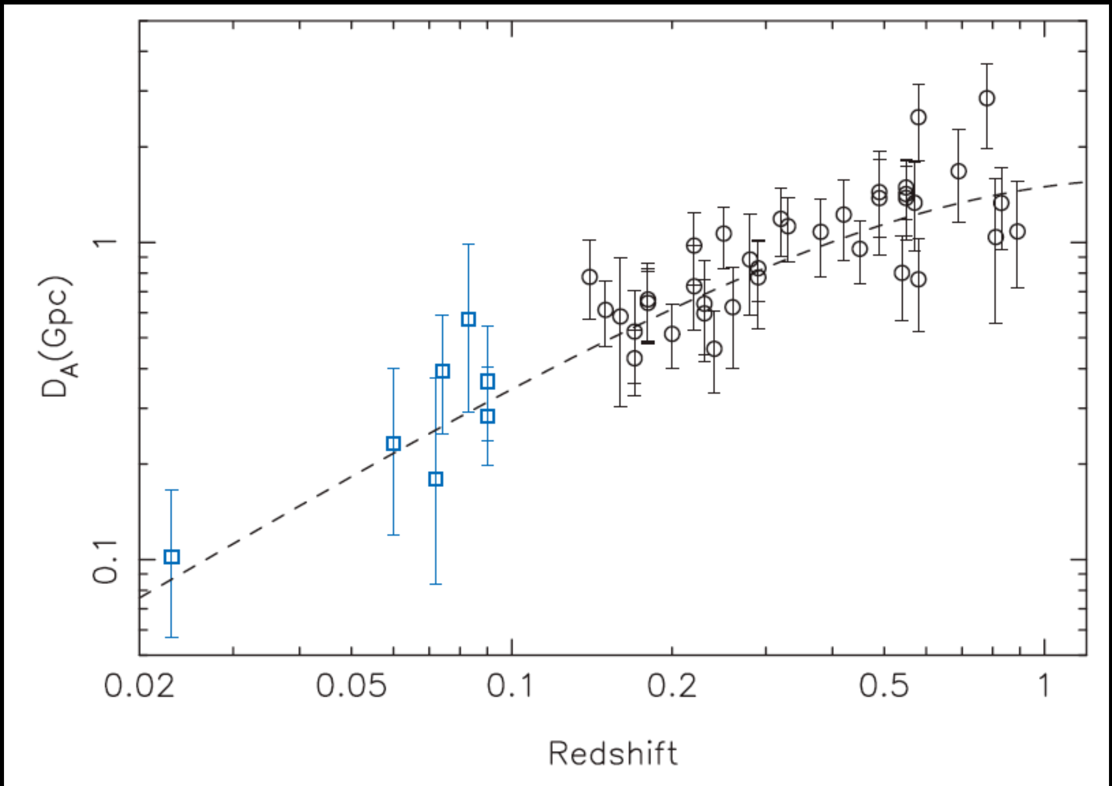
- Characteristic scale of cluster along LOS related to scale in plane of sky (symmetry)

    Probably true in absence of selection effects

- $\langle n_e \rangle^2 = \langle n^2{}_e \rangle$ along LOS (C = 1)

    If this is not true, $H \sim C^2$

Results



Fit for 38 clusters (circles)
dashed line: best-fit assuming Ω_m=0.3 Ω_Λ=0.7

Bonamente et al. 2006, ApJ, 647, 25-54

38 clusters measured in SZE (OVRO/BIMA) and X-ray (Chandra) over $0.14 \lesssim z \lesssim 0.89$

H_0 = 76.9 km/s/Mpc (+- ~12 km/s) assuming Ω_m=0.3 Ω_Λ=0.7

(WMAP III best-fit: H_0 = 70.4, Ω_m=0.268 Ω_Λ=0.732)

H, D_A measurements: the future

- Statistical errors to be reduced: lots of clusters will be observed in both SZE, X-ray in near future
- Systematic errors all being examined:
  - departure from isothermality
  - clumping (substructure)
  - point source contamination of SZE
  - See Birkinshaw (1999), Reese et al. (2000, 2002)

Cluster gas mass fraction

- The ICM contains most of the baryons within a cluster: f_g a reasonable approx. of baryonic mass fraction of cluster
- f_g should also be approximately the universal mass fraction, $f_B \equiv \Omega_B/\Omega_M$ (really, $f_g \leq f_B$)
- $f_B \rightarrow \Omega_M$, given prior knowledge of Ω_B (from BBN)

How do we get f_g?

- Get M_g directly from SZE, assuming T_e is known (recall integrated SZE ~ $M_g \langle T_e \rangle / D_A^2$)
- Get M_{tot} by assuming hydrostatic equilibrium + observed gas distribution + T_e (or strong/weak lensing)
- Combined, this tells us $f_g \sim \frac{\Delta T_{SZE}}{T_e^2}$

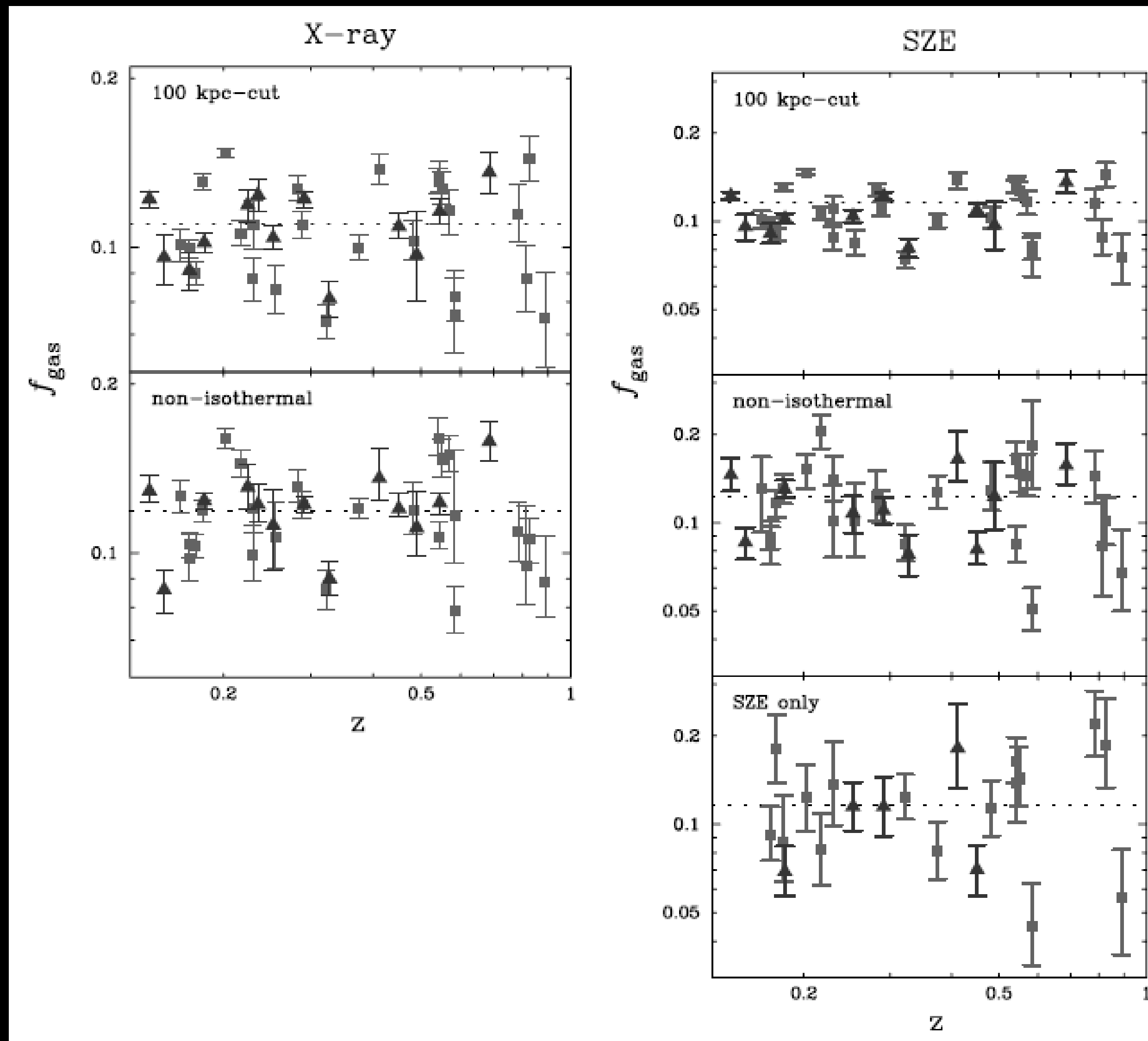
Recent results: LaRoque et al. 2006, ApJ, 652, 917

Chandra + OVRO/ BIMA data

38 galaxy clusters at $0.14 < z < 0.89$

multiple fits to data

results agree with standard LCDM



Problems with this method

- Observations strongly depend on X-ray, SZE systematics
- The assumption of hydrostatic equilibrium is a very dangerous one (and generally wrong - see later discussion)
- Standard isothermal, beta-model fits of density, temperature profiles are not accurate (Hallman et al. 2007; astro-ph/0705.0531)
- f_g probably does not represent the cosmic mean at the 10% level (messy astrophysics)

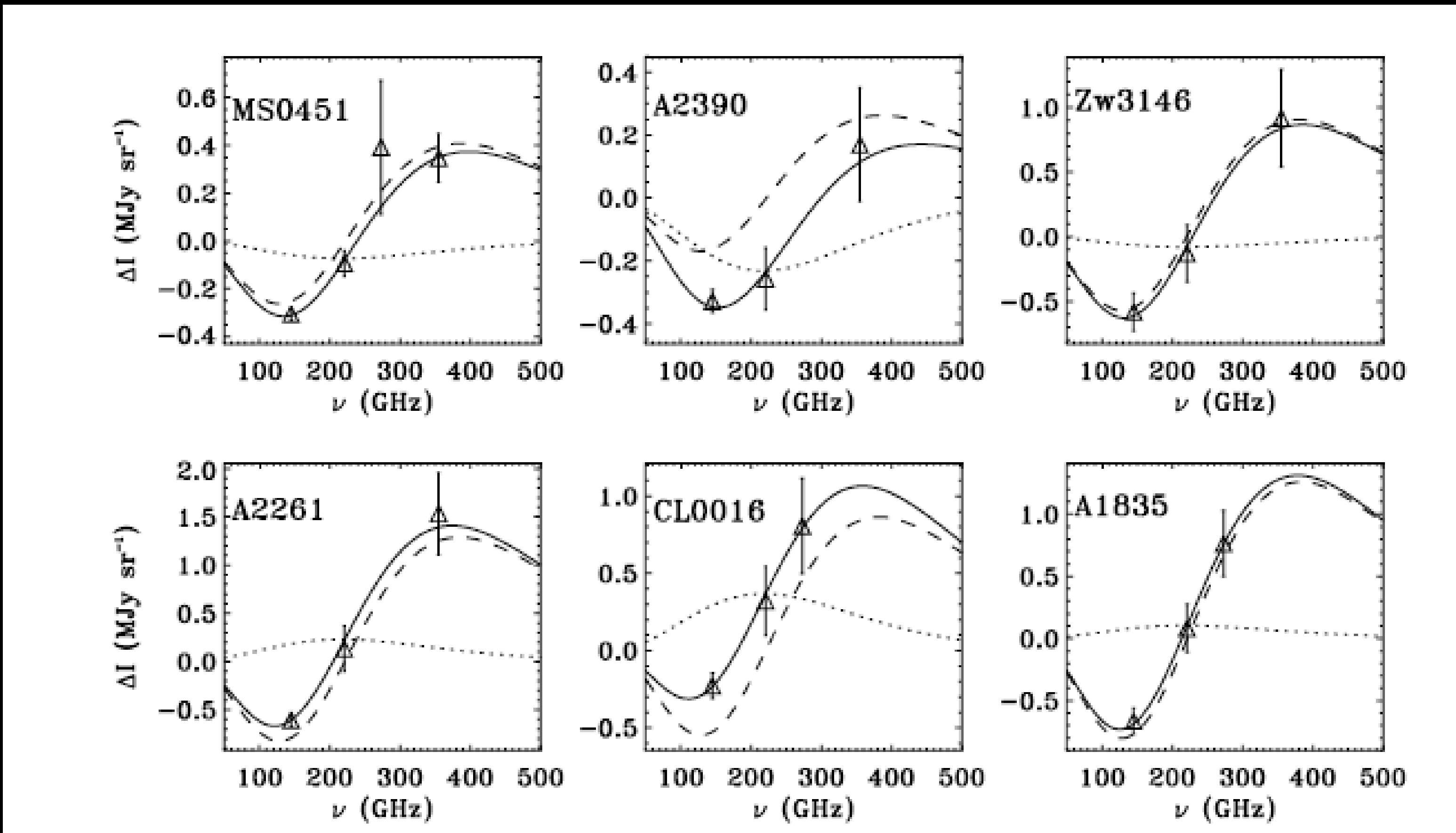
Cluster peculiar velocities

- kinetic SZE: only known way to measure large-scale velocity fields at high z
- cluster PV stats can constrain fundamental cosmological parameters - see talk later today by S. Bhattacharya
- sensitive multifrequency SZE obs'ns required to separate thermal, kinetic SZE (but possible w/ Planck)
- challenging due to contamination from CMB temperature fluctuations, other sources - however, averaging over many clusters may help

Recent(ish) results: Benson et al. 2003, ApJ, 592, 674-691

- Made measurements of six galaxy clusters at $z > 0.2$ using the SuZIE II SZE experiment
- Observe simultaneously at 3 frequency bands (centered on 145, 221, 355 GHz)
- Use measurements at these three bands, back out separate thermal, kinetic SZE components

Recent(ish) results: Benson et al. 2003, ApJ, 592, 674-691



Recent(ish) results: Benson et al. 2003, ApJ, 592, 674-691

TABLE 6

Summary of Results

Cluster	Date	ΔR.A. (arcsec)	$y_0 \times 10^4$	v_{pec} (km s^{-1})
A2261	1999 Mar	$6.4^{+18.6}_{-19.5}$	$7.41^{+1.95}_{-1.98}$	-1575^{+1500}_{-975}
A2390	2000 Nov	$-4.8^{+18.1}_{-19.1}$	$1.72^{+1.01}_{-0.76}$	$+1900^{+6225}_{-2650}$
Zw 3146	2000 Nov	$11.4^{+30.9}_{-30.9}$	$3.62^{+1.83}_{-2.52}$	-400^{+3700}_{-1925}
A1835	1996 Apr	$28.0^{+16.0}_{-15.0}$	$7.66^{+1.64}_{-1.66}$	-175^{+1675}_{-1275}
Cl 0016	1996 Nov	$6.2^{+34.5}_{-37.4}$	$3.27^{+1.45}_{-2.86}$	-4100^{+2650}_{-1625}
MS 0451	1996 Nov	$-15.5^{+26.0}_{-24.0}$	$3.20^{+1.61}_{-1.61}$	$+175^{+5750}_{-2625}$
	1997 Nov	$12.0^{+10.0}_{-11.0}$	$2.07^{+0.70}_{-0.72}$	$+1775^{+3900}_{-2150}$
	2000 Nov	$-21.5^{+21.0}_{-19.0}$	$3.17^{+0.86}_{-0.88}$	-300^{+1950}_{-1275}
Combined fit for MS 0451			$2.84^{+0.52}_{-0.52}$	$+800^{+1525}_{-1125}$

Recent(ish) results: Benson et al. 2003, ApJ, 592, 674-691

- Peculiar velocity values are really upper limits (given fitting method)
- Can use cluster sample to set limit on bulk flow in direction of CMB dipole: < 1420 km/s at 95% CL
- Systematic uncertainties in peculiar velocity determination most likely dominated by submm point sources

Outline

(1) Some background: the CMB, inverse Compton scattering, galaxy clusters

(2) The Sunyaev-Zel`dovich Effect

(3) Cosmological probes

(4) Upcoming SZ observational campaigns

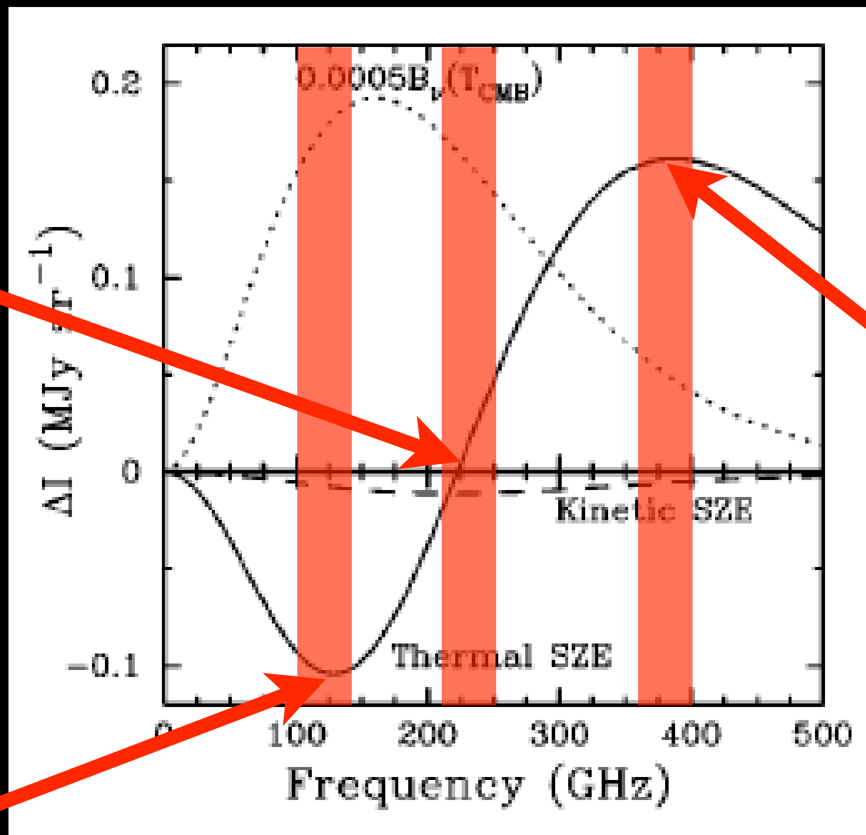
(5) Simulations of the SZE

Upcoming SZE obs. campaigns

- As discussed previously, the SZE can be a powerful cosmological probe
- Several SZE-specific mm-wave survey telescopes are currently under construction/ seeing first light
- Will discuss ONLY single-dish telescopes in this section (see S. Myers talk from Monday re: uses of interferometers)

First, a comment on SZE observations...

zero point (~218 Ghz / 1.4 mm)

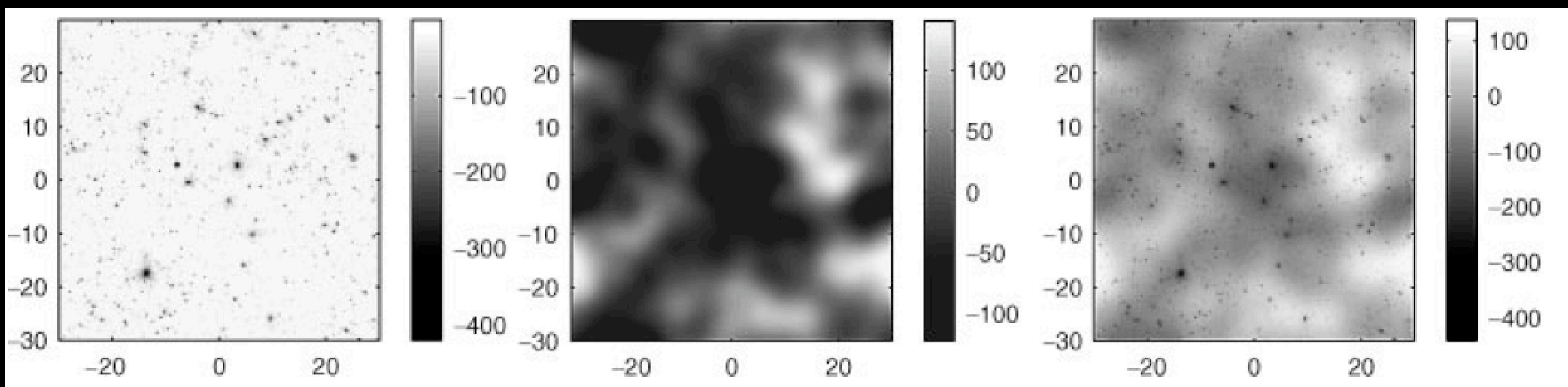


increment maximum (~380 Ghz / 0.79 mm)

decrement maximum (~144 Ghz / 2.1 mm)

Optimum bands to observe thermal SZE!

Disentangling the SZE from primary CMB fluctuations



SZE @ 150 GHz

Primary CMB anisotropies @ 150 GHz

SZE + CMB @ 150 Ghz

Image from Carlstrom et al. 2002, ARAA

Image 1 deg^2

Atacama Pathfinder Experiment SZ telescope (APEX-SZ)

- Collaboration between MPIfR, Onsolo Space Observatory, ESO
- Located in the Atacama desert in Chile: elev. 5100 m
- modified ALMA prototype antenna; 12 m dish
- Obs. at 1.4, 2 mm (218, 144 GHz) with beam FWHM of 1.0’ and sensitivity of 10 μK @ 144 GHz
- Survey ~200 deg^2 over two seasons - online now!
- http://www.apex-telescope.org/

South Pole Telescope (SPT)

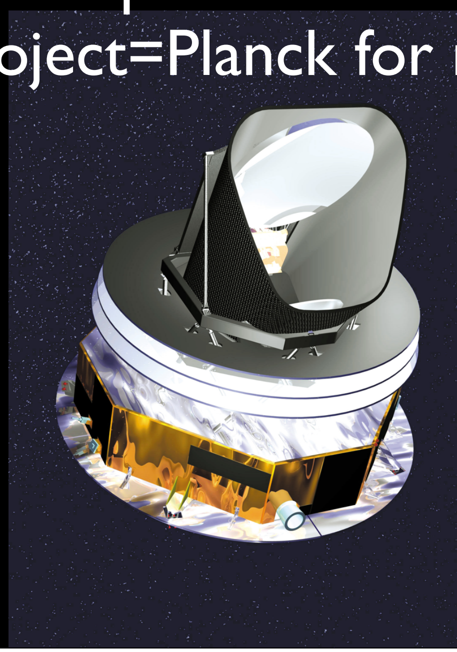
- Collaboration of various US universities, lead by U of Chicago
- Located at South Pole, completed Jan. 2007 (First light Feb. 16, 2007)
- 10m primary mirror, very sensitive bolometer array
- Survey ~4000 deg^2 over 1-3mm (~100-300 GHz) range (90, 150, 220, 270 GHz channels)
- Beam FWHM of 1.0’ and sensitivity of 10 μK @ 150 GHz
- http://spt.uchicago.edu/

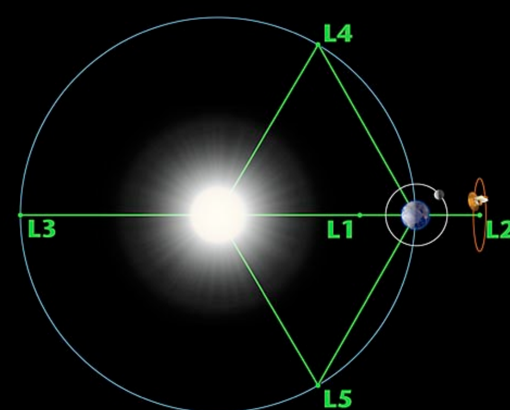
Atacama Cosmology Telescope (ACT)

- International collaboration: US, Canada, Mexico, Chile, South Africa, UK
- Telescope located in Atacama Desert, Chile (elev. 5100 m),
- Observe 2 deg. strip x 50 deg. long (100 deg^2) at 150, 220, 270 GHz over 2 years (First light late 2007)
- Beam FWHM of 1.0' and sensitivity of 2 μK @ 150 GHz
- http://www.physics.princeton.edu/act/

Planck Surveyor

- Satellite mission funded by ESA
- Launching July/August 2008, final location L2
- nominal mission length 12-14 months (on-station), results in 2010
- see http://www.rssd.esa.int/index.php?project=Planck for more details





Planck Surveyor

- 1.5m telescope (satellite), observing whole sky in 30-875 GHz frequency range (30, 44, 70, 100, 143, 217, 353, 545, 875 GHz) - including polarization!
- Resolution 7.1' @ 143 GHz, sens. 6 μK RMS/beam
- Measure y in > 10^4 clusters
- Measure bulk velocities of LSS (scales > 300 Mpc) out to z ~ 1 with dv ~ 50 km/s
- Estimate H_0 from SZE, X-ray

Side-by-side comparison of single-dish SZE experiments

	Sky coverage (deg^2)	Beam FWHM @ 144 GHz (arcmin)	RMS/Beam (μK)
APEX-SZ	200	1.0	10
SPT	4000	1.0	10
ACT	100	1.7	2
Planck	All-sky	7.1	6

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(5) Simulations of the SZE

Why do we need simulations?

- “Precision cosmology” requires estimates of cluster mass (as it relates to observables) to high (percent-level) accuracy
- Analytic models typically assume clusters are very simple: hydrostatic, spherical, simple temperature profiles (isothermal or beta-model) and have limited physics
- We need to understand scatter+bias in SZE, X-ray, optical observables due to non-ideal (“realistic”) GCs in order to calibrate observations
- In general, fewer assumptions in simulations than in analytic models - more useful for comparing to observations!

What can we *do* with simulations?

- Test scaling relations between observables and intrinsic cluster properties (e.g. L, T, y_0, y_{500}, Y vs. M_{gas}, M_{tot}, C, ...) and also potential *bias and scatter* in each observable
- Test the impact of dynamical events and non-ideal properties of clusters (mergers, asphericity) as well as the impact of new physics (gas, cooling, SF+FB, CRs, AGN, B-fields, conduction, etc...) on cluster properties (e.g. Pfrommer talk on Tuesday)
- Make mock observations to test analysis pipelines, etc. - can we get out the cosmology we put in?

Some examples of galaxy cluster simulations...

(an embarrassingly incomplete list)

Cluster SZE scaling relations

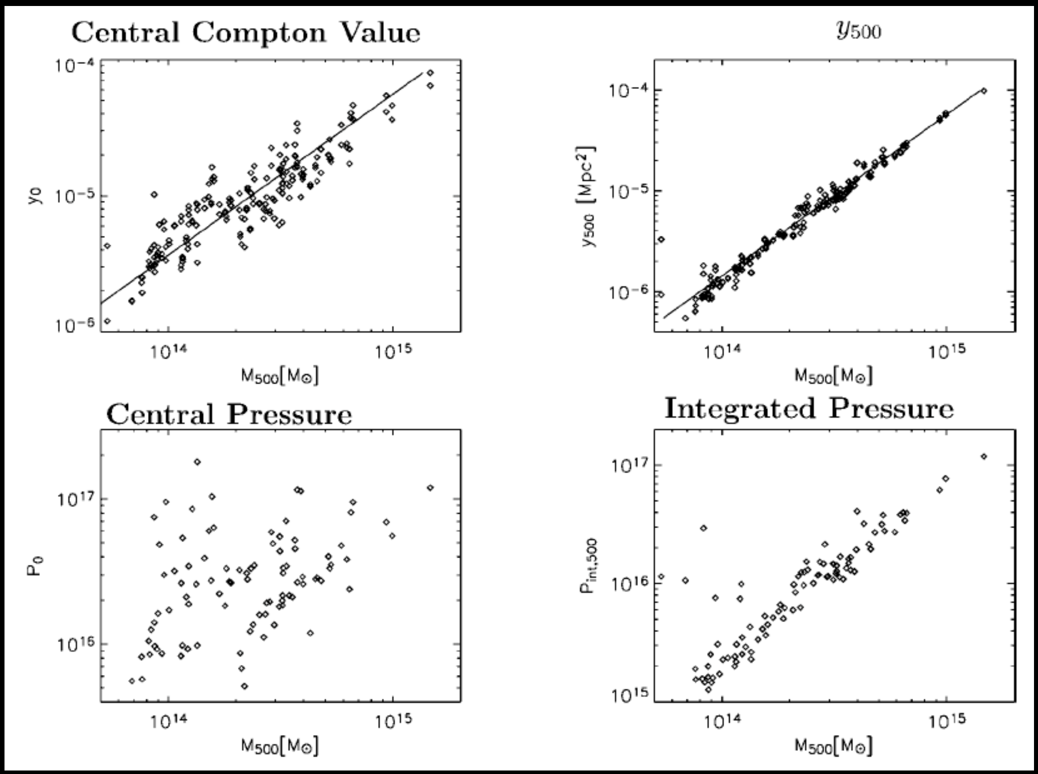


TABLE 1

SCALING EXPONENT FOR y_{500}-M RELATION, $z = 0$

Simulation	α	σ_α
Adiabatic	1.59	0.021
Radiative cooling	1.71	0.031
Star formation	1.60	0.027
Star formation with feedback	1.61	0.024

TABLE 2

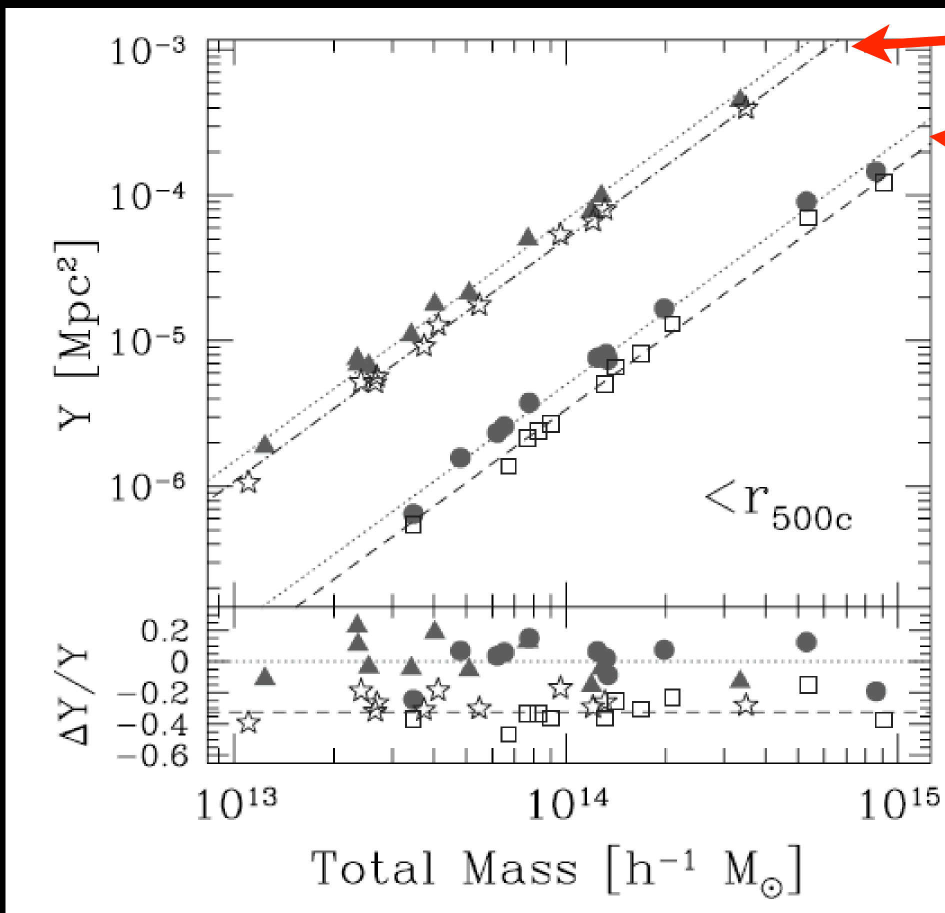
ACCURACY OF MASS ESTIMATION, $z = 0$

Method	Median M_{est}/M_{true}	$+1\,\sigma$	$-1\,\sigma$	+80%	−80%
y_{500}-M	0.97	1.00	0.93	1.13	0.86
T_X-M	1.04	1.11	0.92	1.33	0.74
$L_{X,500}$-M	0.87	1.03	0.75	1.46	0.62
y_0-M	0.96	1.14	0.82	1.53	0.67

$10^{14} \lesssim M_{cl} \lesssim 2\times10^{15}\ M_\odot$

Motl et al. 2005, ApJ, 623, L63-66

Cluster SZE scaling relations



z=1

z=0

$$Y^{\text{int}} \propto \begin{cases} f_{\text{gas}} M^{5/3} E^{2/3}(z) \\ f_{\text{gas}} T^{5/2} E^{-1}(z) \end{cases}$$

Filled points: adiabatic
Open: star formation+FB

Deviation from best
fit to adiabatic runs

Nagai 2006, ApJ, 650, 538-49

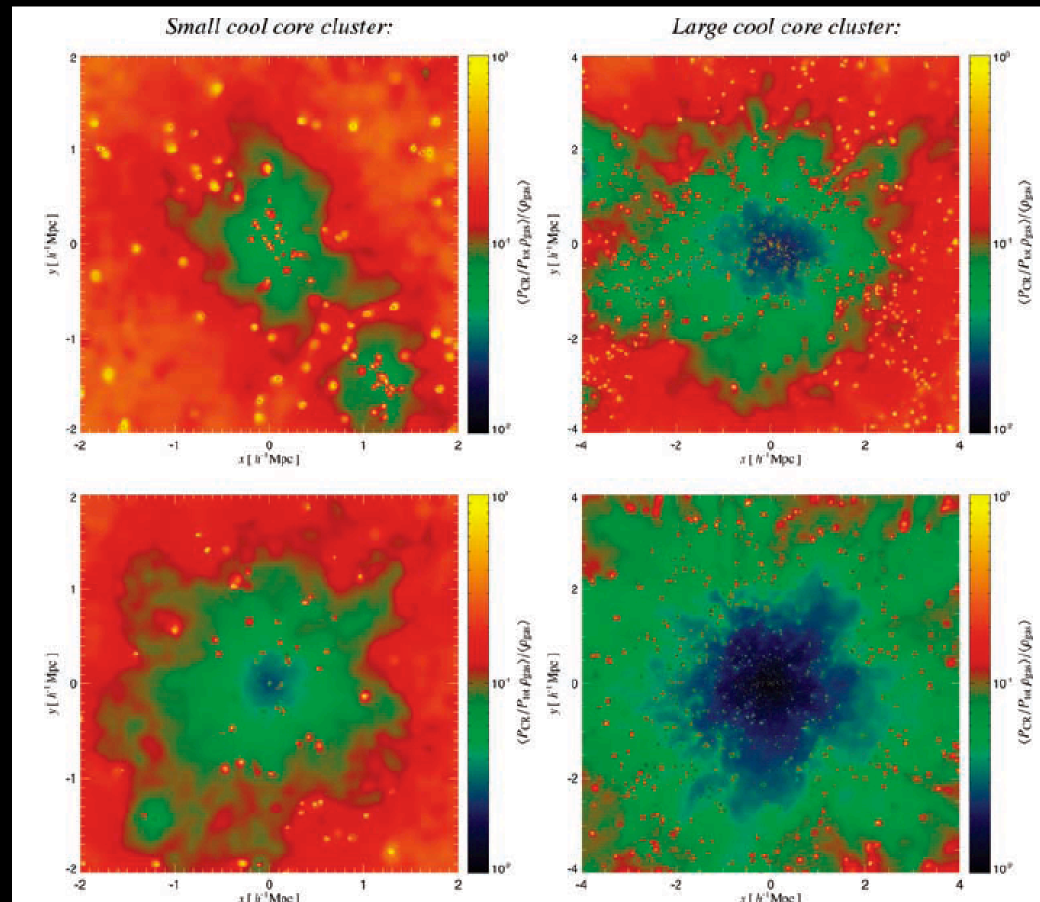
Impact of new physics

Cosmic rays

Shown: mass-weighted CR pressure relative to total pressure for two cool-core clusters, including CRs from structure formation shocks

z=1

z=0

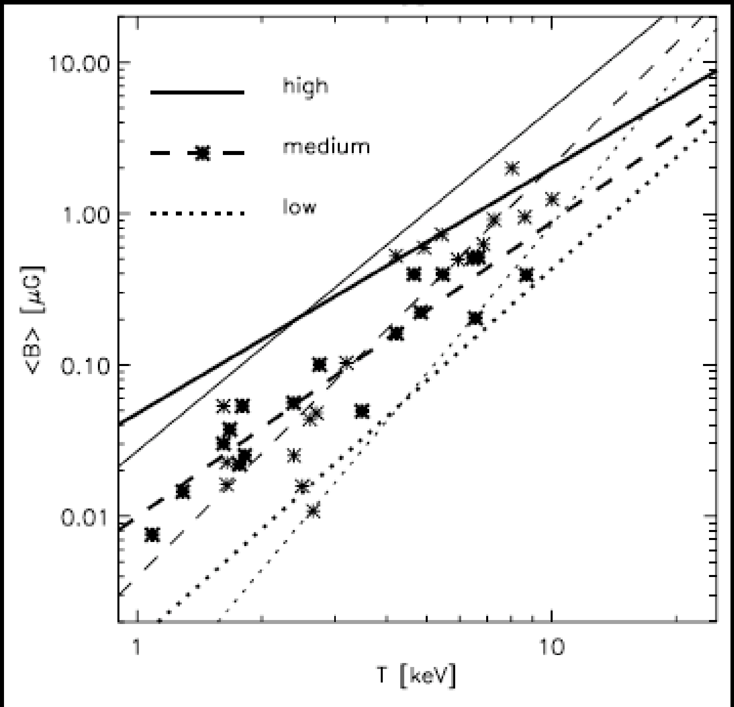


$8.8 \times 10^{13}\ h^{-1}\ M_\odot$ $1.8 \times 10^{15}\ h^{-1}\ M_\odot$

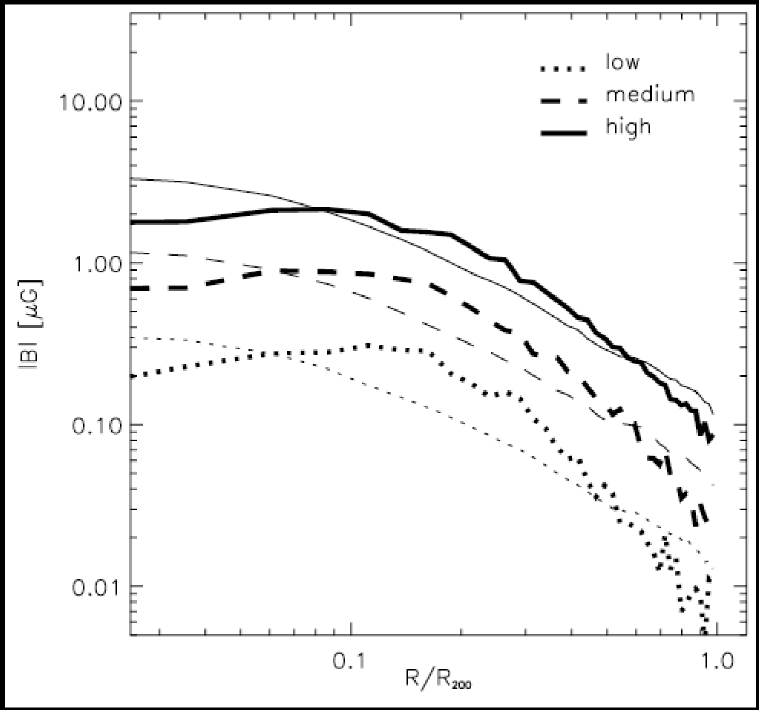
Pfrommer et al. 2007, MNRAS, 378, 385-408

Impact of new physics

Magnetic fields



Mean B-field as fctn
of cluster temp.



Mean B-field as fctn
of radius

Dolag et al. 2002, A&A, 387, 383-95

Light cone mockups
(observing the simulated universe)

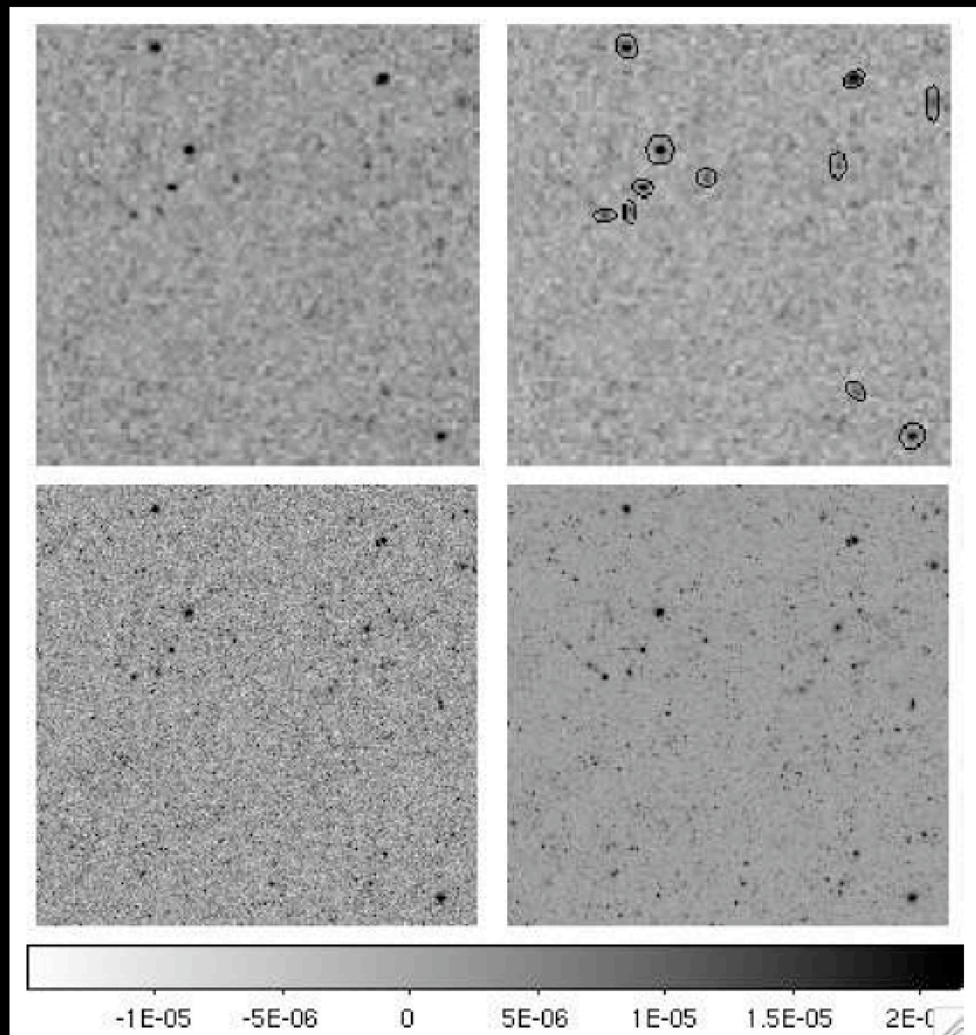
- Hallman, O’Shea et al. 2007, ApJ sub. (astro-ph/0704.2607)
- 5123 RG, 512 Mpc/h box
- Run to z=0 using Enzo w/7 levels of AMR (7.8 kpc/h comoving max resolution)
- Physics: dark matter + adiabatic gas
- Create light cones by stacking data outputs w/random axis choice, spatial shifts
- Degrade “ideal” light cones in resolution to match upcoming SZE experiments, add noise, analyze!

Light cone mockups
(observing the simulated universe)

100 deg^2 field

Planck

APEX/SPT

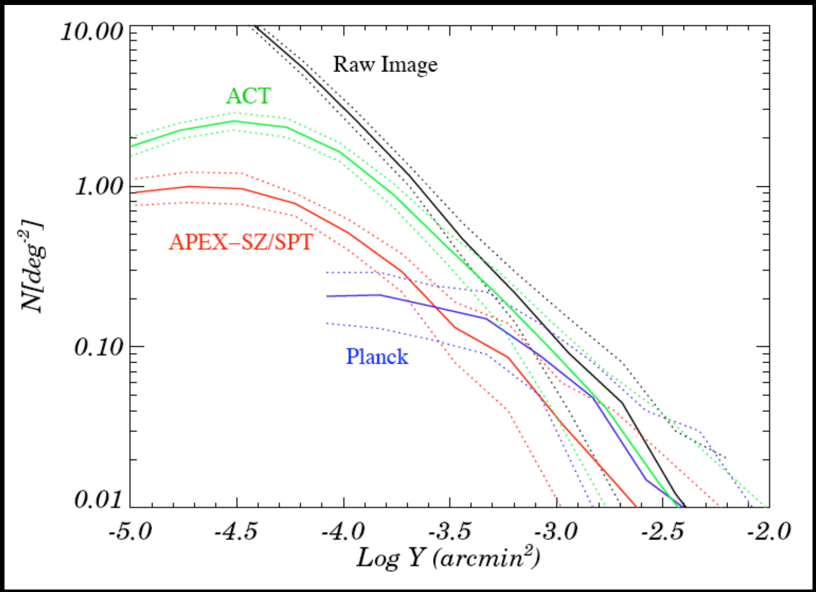


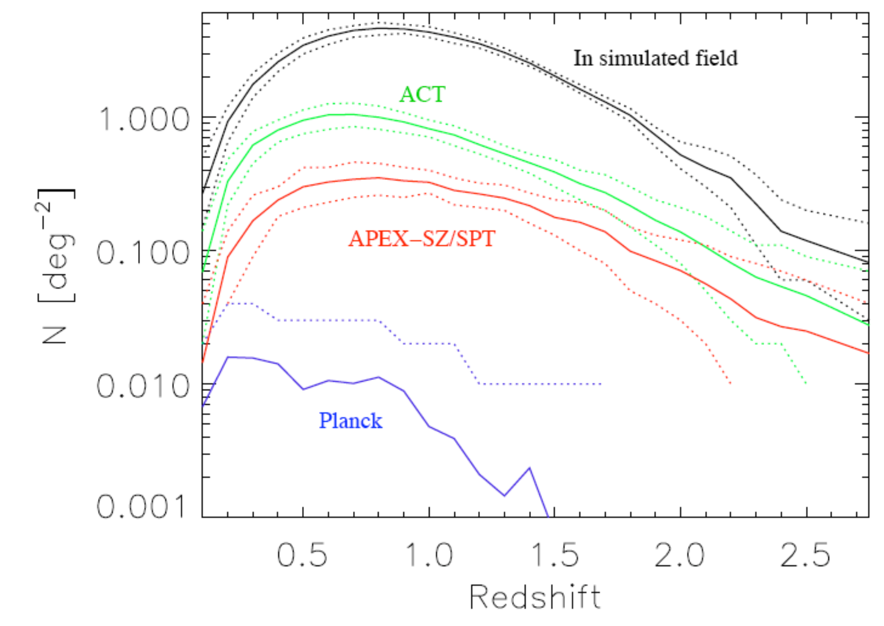
Planck w/ sources

ACT

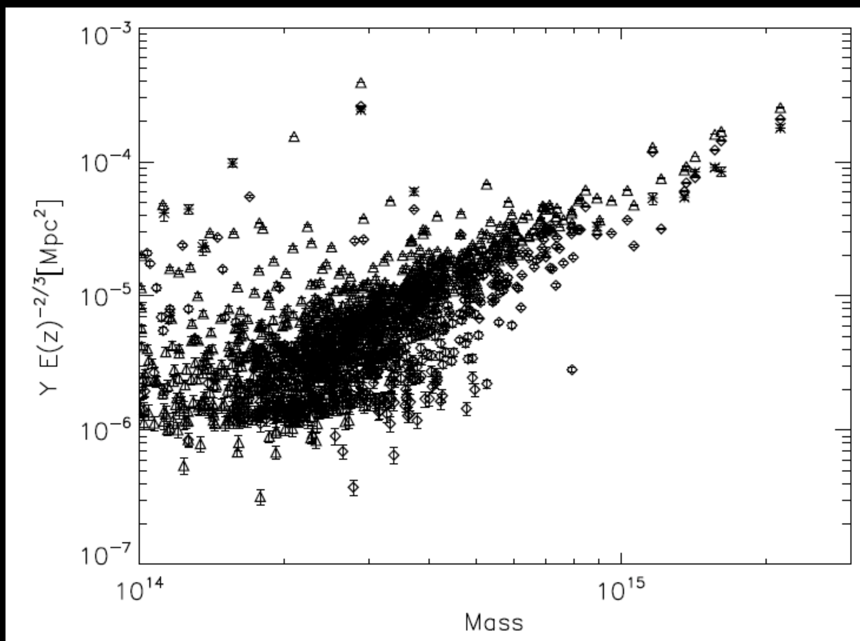
Hallman, O'Shea, et al. 2007, ApJ submitted (astro-ph/0704.2607)

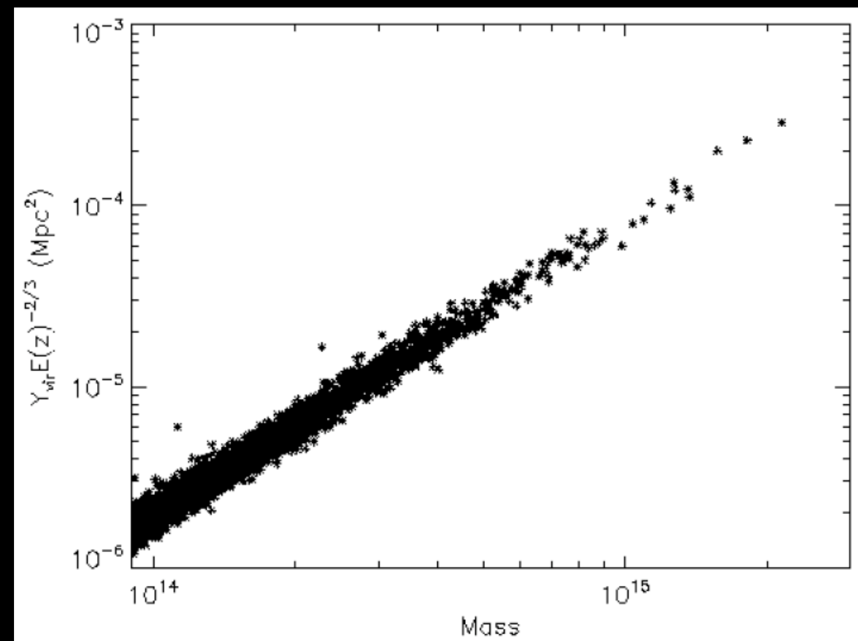
Light cone mockups
(observing the simulated universe)



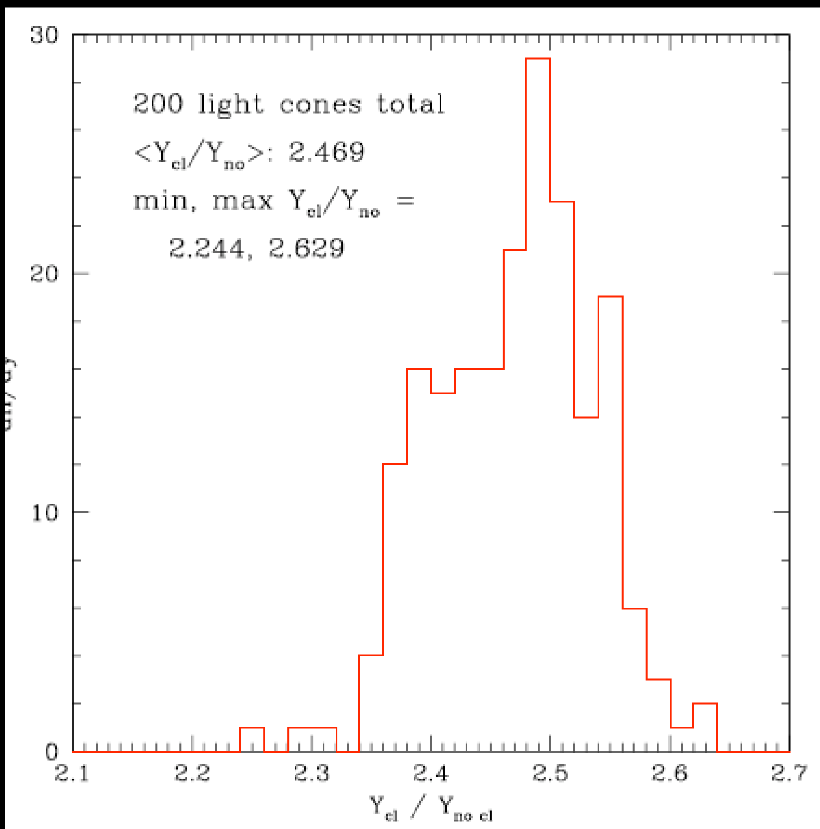


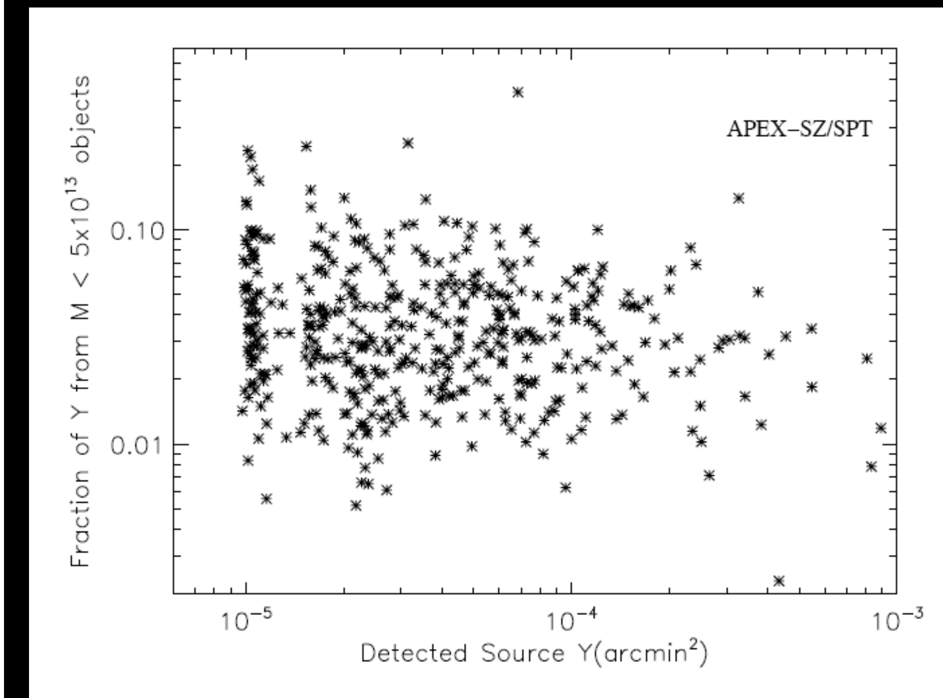
Light cone mockups
(observing the simulated universe)





Light cone mockups
(observing the simulated universe)





Conclusions

1. The Sunyaev-Zel`dovich effect has the potential to be an extremely powerful cosmological probe
2. Multiple facets: thermal SZE, kinetic SZE, polarization
3. The SZE can be used to probe galaxy cluster abundances and evolution (w,Ω_m,σ_8), cluster gas mass fractions (Ω_m), cluster distances (H_0), cluster peculiar velocities (large-scale velocity statistics)

Conclusions

4. Several complementary single-dish observational campaigns are currently underway or will be underway shortly, covering significant fractions of the sky: expect to find thousands of GCs!
5. These campaigns (and most of the cosmological probes discussed) require some sort of followup (optical with photo-z, X-ray) to be useful
6. Simulations show that many simplifying assumptions (spherical shapes, isothermality, hydrostatic equilibrium, etc.) are not true, so caution is needed to interpret SZE results

Conclusions

7. Large-scale numerical simulations can be used to generate mock SZE observations, enabling the testing of data analysis pipelines and potentially uncovering observational challenges/opportunities

Some useful references

- "*Cosmology with the Sunyaev-Zel`dovich Effect,*" Carlstrom, Holder & Reese, 2002 ARAA, 40:643-680
- *"CMB Anisotropies,"* Hu & Dodelson, 2002 ARAA 40:171-216
- "*Comptonization of the CMB: The Sunyaev-Zel`dovich Effect," Y. Rephaeli, 1995 ARAA 33:541-79*